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MHD PLASMA CHANNEL RESPONSE TO PROPAGATING ION BEAMS.(U)
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CONTENTS

MHD PLASMA CHANNEL RESPONSE TO PROPAGATING ION BEAMS.....	1
REFERENCES.....	7

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MHD PLASMA CHANNEL RESPONSE TO PROPAGATING ION BEAMS

Mega-ampere beams of 1-2 MeV protons and deuterons have recently been extracted from 100 cm^2 Pinch Reflex diodes coupled to high-power transmission line generators.¹ Focusing to $.4 \text{ MA/cm}^2$ has been reported.^{1,2} These light ion beams are appropriate for inertial confinement fusion experiments when a large number of them are individually transported several meters and combined onto a pellet.³ To this end, 100 kA/cm^2 beams have been transported a meter distance through 50 kA discharges in 1 torr air.⁴ The azimuthal magnetic field produced by the discharge current confines the charge- and current-neutralized beam within the discharge diameter. In the present theoretical work, the MHD response of transport channels to ignition-system-level beams is investigated. Simple analytic estimates for channel response agree with a 1-D radial, 2 temperature MHD code for moderate density changes. Results indicate that for 3 to 5 MeV protons, mega-ampere-level beams can be transported.

The discharge current I_{ch} required to transport a beam with given injection conditions is determined from conservation of p_z -conical momentum. For an ion entering a discharge at radius r_0 with speed v_0 at angle θ to the z axis with no angular momentum,

$$v_z(r) = v_0 \cos \theta + q_1/m_1 \int_{r_0}^r B(r) dr \quad (1)$$

where B is the azimuthal magnetic field. For proton beams and $B(r) \sim r$, $I_{ch}(A) \approx .5 \cdot 10^{-3} \theta_m^2 v_0$ (cm/s) where θ_m (rad) is the maximum injection angle. For 50 kA discharge currents and several-MeV protons, this expression requires $\theta_m \lesssim 10^\circ$. A uniform current distribution is appropriate for few-electron-volt, centimeter-diameter discharges established microseconds before beam injection. Once the beam is injected into the discharge, kinetic pressure and magnetic forces on the plasma return current induced by beam injection drive channel expansion on the 50 ns beam duration time scale. The expanding plasma convects magnetic field outward, thereby increasing the beam radius. At the same time, the beam experiences energy losses due to collisional deposition and deceleration in induced electric fields. The plasma channel density must be low enough to prevent excessive energy losses but high enough to prevent excessive expansion.

In order to study the response of the channel to injected beams with a 1-D radial code, azimuthal symmetry and small axial gradients are assumed.⁵ The equations solved in the code include the MHD equations with classical electron transport coefficients and the appropriate Maxwell's equations.

$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (\rho r v) = 0 \quad (2)$$

$$\frac{\partial \rho v}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (\rho r v) = - \frac{\partial p}{\partial r} - \frac{j_p B}{c} \quad (3)$$

$$\frac{\partial \epsilon}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} [(\epsilon + p) v + q_e] = Q_e - \frac{v B}{c} j_p \quad (4)$$

$$\frac{3}{2} n_e k \frac{\partial T_e}{\partial t} + \frac{3}{2} n_e v k \frac{\partial T_e}{\partial r} + p_e \frac{1}{r} \frac{\partial}{\partial r} r v + \frac{1}{r} \frac{\partial}{\partial r} r q_e = Q_e - \frac{n_e k}{\tau_{ei}} (T_i - T_e) \quad (5)$$

$$\frac{\partial B}{\partial t} = -c \frac{\partial E}{\partial r} \quad (6)$$

$$\frac{1}{r} \frac{\partial r B}{\partial r} = \frac{4\pi}{c} (j_b + j_p) \quad (7)$$

$$E = \eta j_p - \frac{vB}{c}$$

with

$$\epsilon = \frac{1}{2} \rho v^2 + \frac{3}{2} n_i k T_i + \frac{3}{2} n_e k T_e \quad (9)$$

$$p = n_e k T_e + n_i k T_i \quad (10)$$

$$q_e = -K_e \frac{\partial T_e}{\partial r} \quad (11)$$

$$Q_e = \eta j_p^2 + \rho S j_b - P_{\text{rad}} \quad (12)$$

In the above, j_p and j_b are the plasma and beam current density, τ_{ei} is the electron-ion equipartition time and P_{rad} is the optically-thin radiation loss rate.

The standard channel prior to beam injection is $6 \times 10^{-6} \text{ g/cm}^3$ deuterium ($n_i = 2 \times 10^{18} \text{ cm}^{-3}$), with $I_{\text{ch}} = 50 \text{ kA}$, $T_e = T_i \approx 3 \text{ eV}$ inside a channel of radius $r_{\text{ch}} = 0.56 \text{ cm}$. Deuterium is chosen for simplicity of atomic physics and radiation processes, and for collisional beam losses lower than a comparable mass density of hydrogen. The plasma channel is surrounded by a cold gas blanket. Radial profiles for the channel prior to beam injection (Fig. 1) are derived from pressure balance for I_{ch} uniformly distributed. The transported beam is modeled by $j_b = j_{bo}(t)$ for $r \leq y r_{\text{ch}}$, and $j_b = j_{bo} (1 - r/r_{\text{ch}})/(1 - y)$ for $y r_{\text{ch}} < r \leq r_{\text{ch}}$ with $.1 \leq y \leq .35$. For beam duration τ , $j_{bo} = j_{bm} (1 + t/\tau)/2$. Ion energy ϵ_b increases in time

like j_{bo} , reaching ϵ_{bm} at $t = \tau$. This energy ramp permits beam power multiplication by axial bunching during transport.

In Eq. 3, the magnetic expansion forces usually dominate over kinetic pressure. Assuming constant radial acceleration due to $j_p B/c$, plasma expansion is approximated by

$$\chi \simeq 3 \times 10^{-2} j_b (A/cm^2) j_{ch} (A/cm^2) t^2 (s) / \rho (g/cm^3) \quad (13)$$

where a fluid element initially at radius r is displaced to $(1 + \chi)r$ at time t , j_{ch} is the discharge current density and $j_b \simeq -j_p$ is assumed for $j_{ch} \ll j_b$. Radial channel and beam expansion will be small when $\chi \ll 1$. The standard channel parameters give $\chi \simeq 1/2$ after 50 ns for a 1 MA/cm^2 beam.

Ion compressional heating in Eq. 4 is always less important than the electron-heating mechanisms on the right-hand side except at the channel boundary. For $\epsilon_b = 5 \text{ MeV}$ and $j_b = 1 \text{ MA/cm}^2$, collisional deposition dominates over return-current heating above 3 eV. The proton stopping power in deuterium is then $S = 10^3 / \epsilon_b \text{ MeV/g/cm}^2$. The associated temperature rise in the plasma is $\delta(T_e + T_i) \sim 7 \times 10^3 j_b t / \epsilon_b$ and is of order 100 eV for the above beam after 50 ns. For 2.3-meter transport, collisional beam energy losses are less than 20% of the initial beam energy when $\rho \leq 9 \times 10^{-7} \epsilon_b^2$. This criterion combined with that for inertial confinement (Eq. 13 with $\chi \leq 1/2$) yields $7 \times 10^{-6} \leq \rho \leq 9 \times 10^{-7} \epsilon_b^2$, i.e. $\epsilon_b > 2.8 \text{ MeV}$. Energy losses due to deceleration in the axial electric field of Eq. 8 must also be considered. Early in time, E is established by return-current flow in the resistive plasma. Later, high plasma conductivity and expansion velocity cause the hydrodynamic term to dominate. Energy losses due to

late-time electric field are comparable to collisional losses for the above density regime.

Figure 2 shows the channel at 50 ns for $j_{bm} = .6 \text{ MA/cm}^2$, and $E_{bm} = 5 \text{ MeV}$. Expansion has reduced the initial density to $1.2 - 1.4 \times 10^{18} \text{ cm}^{-3}$. This agrees with the calculated value of $\chi = .3$ from Eq. 13. A figure of merit for ion confinement is defined by the integral in Eq. 1 extended from 0 to r_{ch} . The code calculates a reduction in its value from an initial 5 kG·cm to 3.3 kG·cm for Fig. 2 in agreement with simple scaling. At the conditions shown, transported ions lose about .14 MeV/m collisionally and about .1 MeV/m due to electric-field deceleration. Early in time, when $E_b = 2.5 \text{ MeV}$, corresponding values are .28 MeV/m and .03 MeV/m.

Figure 3 illustrates the response of the standard channel to a beam of comparable power density as in Fig. 2 but with $j_{bm} = 2.75 \text{ MA/cm}^2$ and $E_{bm} = 3 \text{ MeV}$. This case is very different from the preceding one since the channel has had time to expand and to bounce from the cold gas blanket. The structure of the various fluid quantities is much more complicated and indicates that different physics applies. For example, instabilities might play an important role which would change the results quantitatively. Estimates from Eq. 13 can still be made, but only within a radius of about 2 mm where plasma expansion still occurs. In that region, the code is in agreement with simple estimates. An interesting feature of these results is that the vB/c term gives an electric field which will accelerate the ion beam if it exceeds the collisional slowing down (ohmic electric fields are small due to high conductivity).

In addition to the case of the unbunched beam which prevails at the beginning of the channel, the plasma channel response to a bunched beam near the exit of the channel has been investigated. It is found that a beam of a

given current and voltage is more easily transported in its bunched state due to the reduced hydrodynamic expansion. This can be seen from Eq. 13 with $j_b t$ constant so that χ depends only on $j_{ch} t / \rho$. For the 10 ns pulse duration of a bunched beam, the radial expansion is 5 times smaller. Alternatively, the density can be chosen smaller to maintain a constant χ . For constant collisional losses in transit through the channel (i.e. $\int \rho dz = \text{const.}$), the density at the beginning of the channel can then be increased to reduce the channel expansion there.

In conclusion, the hydrodynamic plasma response to light-ion beams has been studied using simple estimates and numerical solutions. For 3-5 MeV proton beam propagation, deuterium z-discharges were studied for injected MA/cm^2 , 50 ns beams. Discharge channel densities $\sim 10^{-5} \text{ g/cm}^3$ were found to permit transport of these beams in both unbunched and bunched states over the several-meter distances required for ICF ignition experiments.

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5. Azimuthal symmetry applies for symmetric beam injection from Pinch Reflex diodes since no external magnetic fields are employed. Small axial gradients exist because of the shallow injection angles required by modest channel current. Additionally, the channel is kink-mode stabilized by the sense-background gas. See for example, W. M. Manheimer, M. Lampe and J. P. Boris, Phys. of Fluids, 16, 1129 (1973).

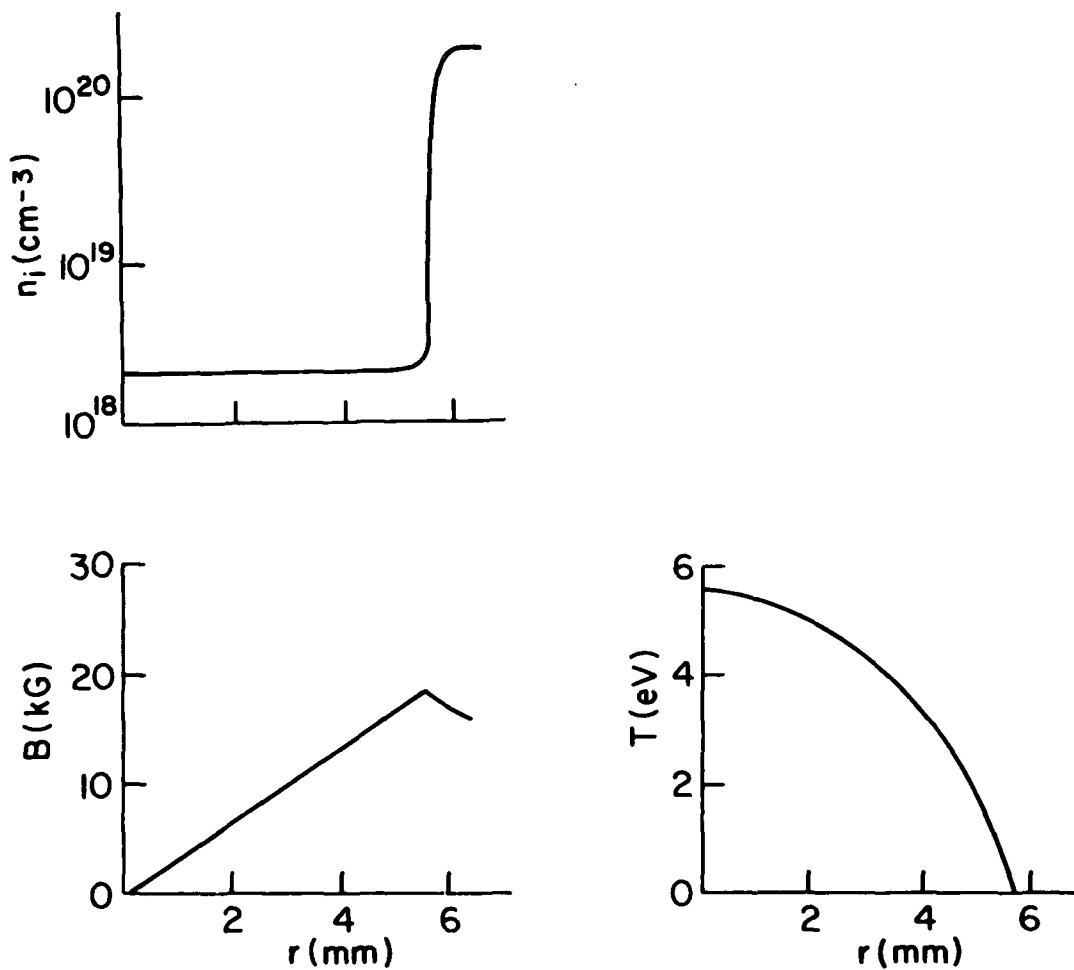


Fig. 1 — Initial deuterium plasma channel conditions corresponding to uniform current distribution and to pressure balance between the channel and cold gas blanket.

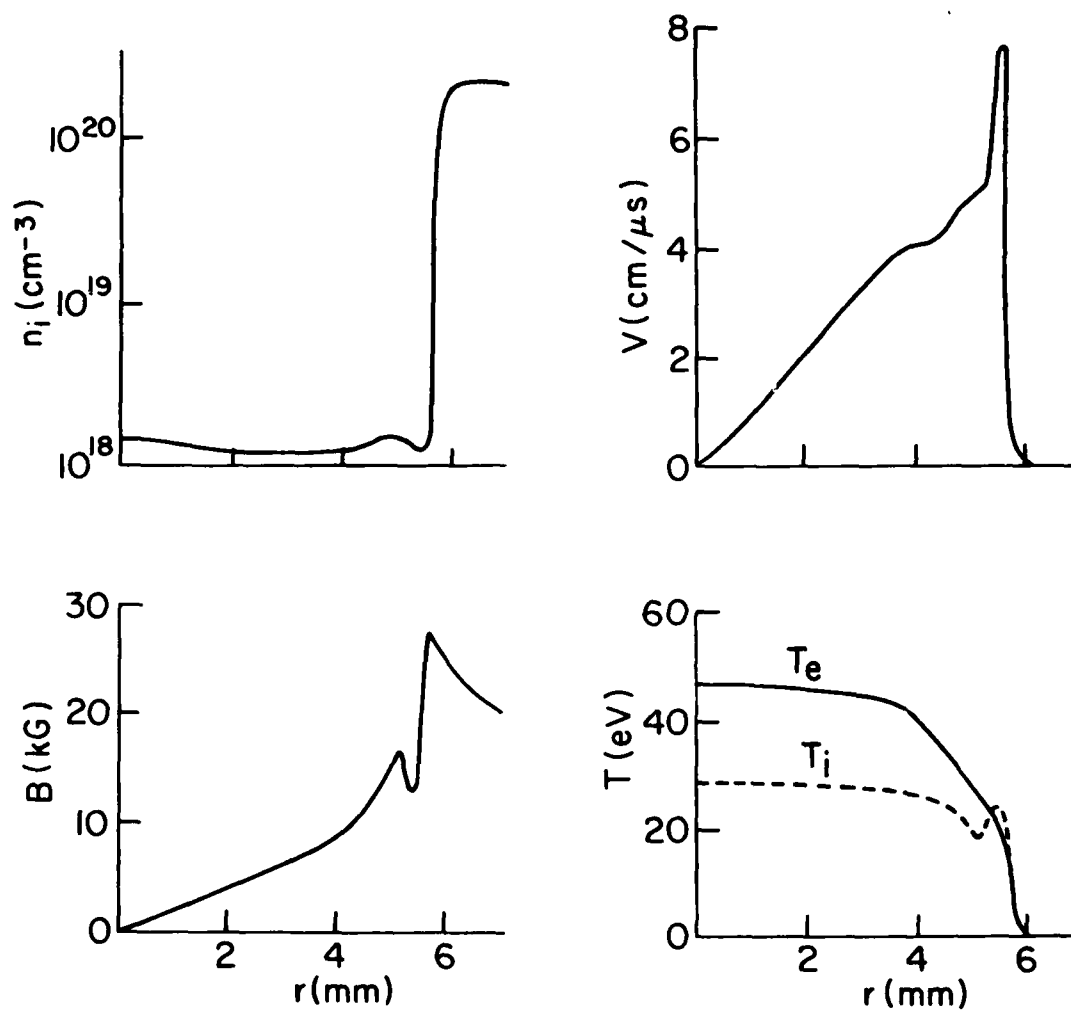


Fig. 2 — Plasma channel characteristics at $t = 50$ ns after injection of a 5 MeV, 400 kA proton beam.

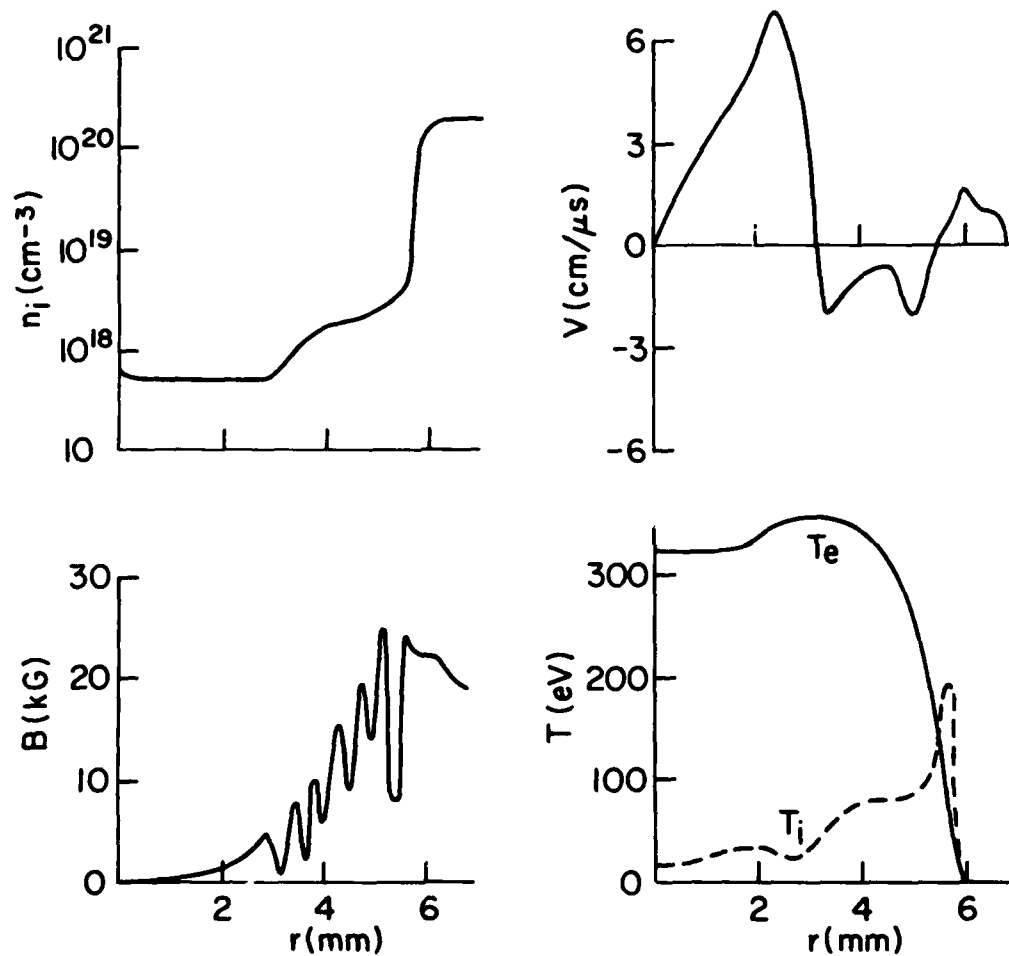


Fig. 3 — Plasma channel characteristics at $t = 50$ ns after injection of a 3 MeV, 2 MA proton beam. Note that the velocity profile indicates reflection from the cold gas blanket.

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